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U.S. Naval Air Development Center

Johnsville, Pennsylvania

Aviation Medical Acceleration Laboratory

NADC-MA-6308 18 October 1963

Pilot Biomedical and Psychological Instrumentation for Monitoring Performance During Centrifuge Simulations of Space Flight

Bureau of Medicine and Surgery
Task MR005.13-6002.4 Report No. 3

Bureau of Naval Weapons
Weptask No. RAE 13J 012/2021/R005 01 01
Problem Assignment No. 012AE 13-19

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SUMMARY

This report presents some of the results of recent centrifuge acceleration research and training projects in which the biomedical, psychophysiological, and psychological performances of pilots were monitored and measured. Monitoring and recording instrumentation techniques are described, and an attempt is made to identify and quantify some of the capabilities and limitations of pilot performance during exposure to accelerations which vary in magnitude, duration, direction, rate of onset, and profile complexity. Apparatus and methods are presented and discussed for monitoring visual disturbance, discrimination and response behavior, complex skill behavior, and an approach is made to the problem of monitoring higher mental functioning. The pilots and other volunteers in these training and research programs were the 7 Mercury astronauts, 6 Dyna-Soar consultant pilots, approximately 35 other test pilots, and approximately 40 other military and civilian volunteers.

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INTRODUCTION

In current research and training programs at the Aviation Medical Acceleration Laboratory (AMAL), pilots and other volunteers receive extensive testing and training within acceleration environments which are usually designed to simulate stressful segments of profiles which may be experienced in various spacecraft during normal launch and reentry maneuvers. Frequently, emphasis is given to possible emergency and escape conditions in which the accelerations may be unusually high, and in which survival may depend largely upon ability to tolerate the acceleration stress and to perform piloting tasks. Based on the results of various centrifuge projects, medical and engineering personnel, as well as the pilots and astronauts themselves, make decisions regarding the cockpit equipment, flight maneuvers, pilot safety requirements and procedures, and training requirements for particular vehicle systems. Consequently, the data upon which these decisions can be based are of major importance during each centrifuge project.

The purpose of this paper is to present some of the results of recent centrifuge acceleration research and training projects in which the biomedical (physiological), psychophysiological, and psychological performances of pilots were monitored and measured. Some of the monitoring and recording instrumentation techniques are described, and an attempt is made to identify and quantify some of the capabilities and limitations of pilot performance during exposure to accelerations which vary in magnitude, duration, direction, rate of onset, and profile complexity. The pilots and other volunteers in these training and research programs were the 7 Mercury astronauts. 6 DynaSoar consultant pilots, approximately 35 other test pilots, and approximately 40 other military and civilian volunteers. The procedures and data reported in this paper are based on joint projects between the AMAL and several NASA, USN, USAF, and other contracting agencies.

DYNAMIC FLIGHT SIMULATION

Many of the physiological and performance problems expected to be encountered in flight may be studied by means of simulation techniques, using centrifuges to produce some of the acceleration conditions of real flight. Unconstrained motion with aircraft and spacecraft involves six degrees of freedom.

The AMAL Human Centrifuge, which has a radius arm of 50 feet, has a 10 by 6 foot oblate spheroid gondola mounted at the end of the arm. The gondola is mounted within the double gimbal system which can continuously position a pilot within the gondola with respect to the direction of any resultant acceleration vector, producing radial accelerations up to 40 G. The gimbal accelerations can reach 10 radians/sec^2 and velocities can reach 2.8 radians/sec. Given this power capability and the proper control, it is possible to simulate the three linear acceleration components of flight continuously and some of the angular accelerations; however, the angular accelerations of the centrifuge with only three degrees of freedom of control cannot simulate all of the possible flight accelerations. After the astronaut enters the centrifuge, the hatch is closed, and the atmospheric pressure may be regulated in order to simulate some of the environmental conditions which may be encountered during normal and emergency flight.

The pilot within the gondola of the centrifuge is provided with an instrument display panel, a control device, and other piloting equipment. He operates his control devices in response to information presented on the instrument panel and cues which he receives during the acceleration. The analog computers are used to close the loop between the pilot, his displays, his controls, and the centrifuge accelerations. Thus, the control movements which the pilot makes are converted into electrical signals and fed into the analog computer, which continuously generates the flight problem and provides solutions which result in output signals. Some of the signal outputs are transformed by a coordinate conversion system at AMAL (Pace 231R analog computer) into appropriate centrifuge control signals which regulate the power voltages to the arm and gimbal system of the gondola. Simultaneously, other signal outputs are fed to the pilot's instruments. When the responses of the pilot are included within the driving mechanism of the acceleration device so that the accelerations he receives from moment to moment vary as a function of his behavior, an interesting type of interaction effect occurs, since the pilot's behavior also varies as a function of the acceleration he experiences.

The pilot-centrifuge-computer system described above consists basically of two closed-loop systems: one connecting the pilot's control responses with the driving system of the centrifuge, and the other connecting the pilot's control responses with the driving mechanisms of the indicators on the pilot's instrument panel (2, 6, and 4.).

This procedure has been used in a number of projects, such as the X-15, Mercury, a number of basic research studies, and X-20.

During a typical simulation program on the AMAL centrifuge, there are from 3 to 9 duty stations at which various types of recordings are taken. These recordings include psychological, performance, medical and engineering data. Sometimes, a large analog computer system records performance error as a function of the programmed task and may, if desired, convert the analog variables to integrated error scores or to digital readouts on IBM cards. Additional data processing systems are available for special purpose analysis. For example, Figure 1 shows a performance monitoring station. At this station, in-line data recording and data processing is provided by feeding the responses through a small analog computer system which simultaneously yields individual means and variability measures of the subject's performance on several task components. Figure 2 shows a block diagram of some of the performance analyses which were done in support of the recent X-20 project.

If programmed to simulate specific types of aerospace vehicles during definite portions of flight maneuvers, the human centrifuge may serve as a very useful tool for identifying and investigating some of the human factors problems associated with a wide variety of the acceleration aspects of flight. The effects of acceleration on pilot physiology, pilot performance and pilot ability to use specific controls, displays, and escape equipment may be investigated. In addition, if the centrifuge is instrumented with appropriate environmental conditions such as atmospheric pressure, pressure suit, oxygen and other gaseous conditions, and computer control of the behavior of both centrifuge and the panel instrument, the centrifuge serves as a very useful tool for studying the effects of combinations of conditions which a pilot may expect to encounter during any given particular acceleration phase of his flight. Finally, the human centrifuge is an extremely useful training device for acceleration aspects of complex flight missions.

To date, most of the simulation programs have been concerned with human factors problems relating to each of three basic types of space vehicles, which are: Type I, a high drag variable lift winged vehicle; Type II, a high drag capsule; and Type III, a glide capsule. During reentry, the pilot in the Type I vehicle is pressed down into his seat; the pilot in the Type II is pressed against the back of his seat; and in the Type III the pilot is pressed against his shoulder straps. At our laboratory, simulations in the first vehicle type have been conducted to acceleration levels as high as $+10\ G_z$; simulations in the second vehicle have gone to as high as $+21\ G_x$; and simulations in the third vehicle have gone as high as $-14\ G_x$.

ACCELERATION TRAINING

The AMAL Human Centrifuge has been found to be a very useful device for astronaut training. Since 1958 it has been one of the major training devices for preparing the Mercury Astronauts for the acceleration phases of their suborbital and orbital space flights. The active Mercury-type instrument panel, Mercury-type side-arm controller, complete environmental

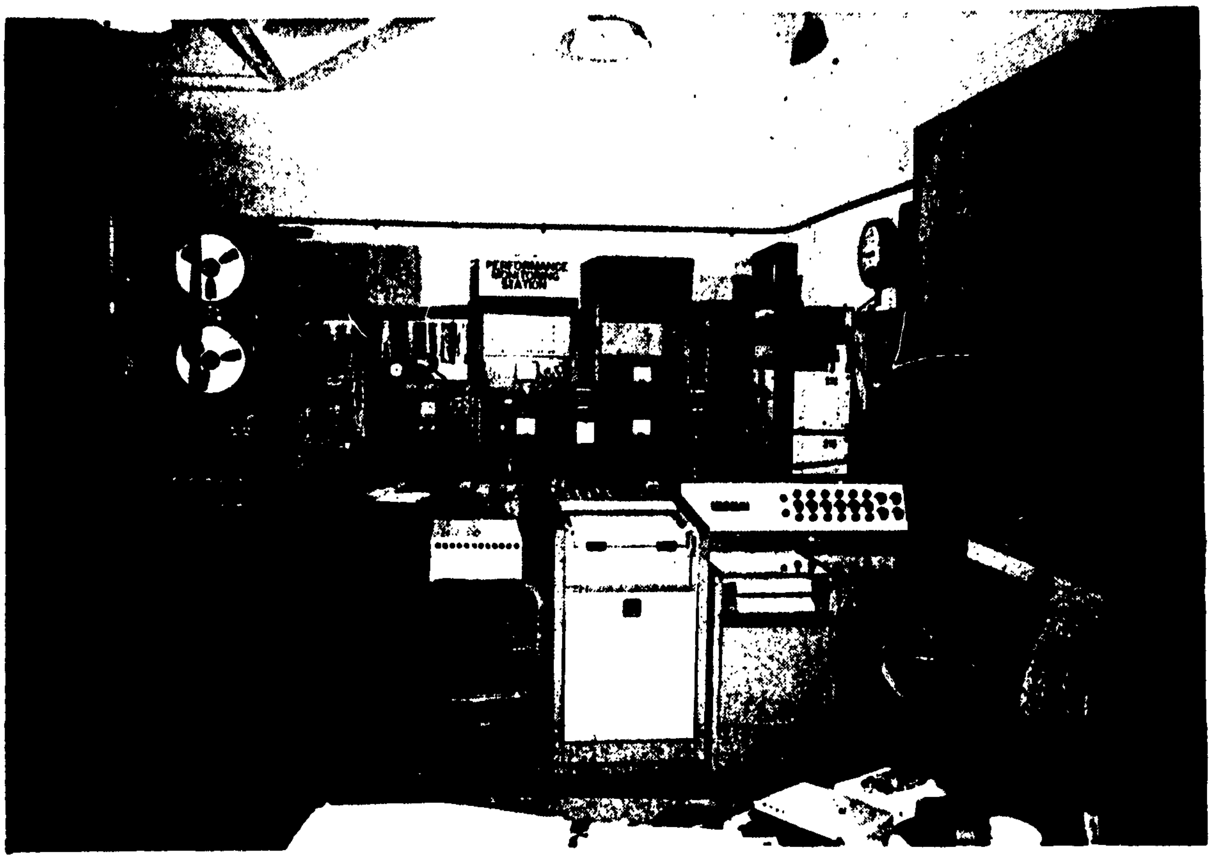

Figure 1. Performance Monitoring Station, Engineering Psychology Laboratory, AMAL.

BUILDING 85 OPERATIONS
PROJECT DYNA-SOAR I

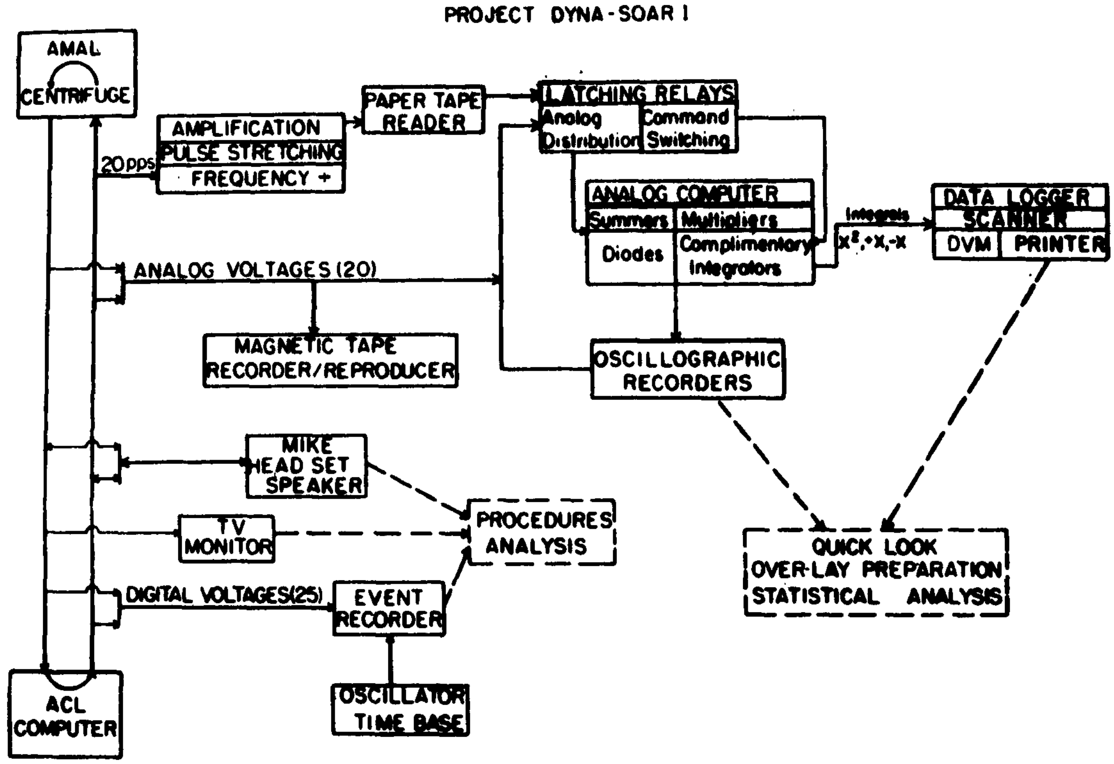

Figure 2. Diagram of Performance Monitoring Station for Project DynaSoar (X-20).

control system, and remotely-controlled centrifuge drive system permitted extensive training on a wide variety of piloting tasks and emergency conditions during exposure to the various acceleration profiles for Redstone, Atlas, and abort maneuvers. The association of telepanel indicator lights with acceleration levels and capsule events constituted a major training effort.

A complete environmental control system, pressure-suit, contour couch restraint system, 100% oxygen, and biosensors were provided. When the gondola was sealed and depressurized to 5 pounds per square inch, the interactions with many different space-flight conditions were experienced by the astronauts. During the course of five training programs at this facility, the astronauts received practice in straining in order to maintain good vision and physiological functioning under high G loads, and in developing breathing and speaking techniques during high G launch, reentry, and abort stress. Experience in tumbling and oscillations during relatively high G exposures was also provided. The astronauts were given extensive practice in controlling their simulated vehicle during reentry and other phases of their simulated flights. They also became skilled in the operation of their environmental control systems and capsule communication procedures during acceleration exposure. Simultaneously, extensive physiological and performance monitoring provided continuous information on astronaut endurance and piloting skill.

Complete mission simulations were presented, beginning with early morning suiting and ending with debriefing, on a real-time basis. This type of simulation permitted physiological and psychological conditioning and man-machine evaluations along real-time scale profiles, and allowed astronauts to experience the many subtle and elusive interactions which occur between the physiological, psychological, and engineering stress variables. Evaluations of the AMAL centrifuge as a training device have been very favorable (25, 18, 19, 24, 20, 29, 28, 3).

The Human Centrifuge has also been found to be useful for providing acceleration experience for the student pilots at the USAF Aerospace Research Pilot's School from Edwards Air Force Base, California. Similarly, the consultant pilots for the X-20 (Dyna-Soar) spacecraft have gone through a series of pilot familiarization and cockpit evaluations to simulate many of the problems expected to be encountered in the X-20 spacecraft.

PROBLEMS IN BIOMEDICAL, PSYCHOPHYSIOLOGICAL, AND PSYCHOLOGICAL MONITORING

The physician, engineer, and psychologist are well aware of the difficulties of selecting and adapting standard biomedical instrumentation methods to measure the effects of acceleration. Often peak G can be maintained for only a few seconds. Standardized tests to measure specific physiological and psychological functioning reliably within such short time intervals are not an actuality. Also, the effects of G on mechanical and electronic apparatus pose serious measurement problems. Furthermore, in some situations, the subject's difficulty in moving, breathing, speaking, and seeing makes test administration by standard apparatus test procedures, interviews, or standard paper-pencil tests, impossible. Finally, achieving reliability and validity during prolonged stress poses a serious problem.

Our survey of available "intelligence" tests, for example, has revealed no standardized ones which are suitable for use within acceleration environments. Even the studies of 16 or so components of human intelligence conducted by Guilford and others on air crews and other special population groups do not provide any feasible or practical intelligence tests which may be used within these environments (8). Demaree pointed out in a recent symposium on this subject (10), that it would be extremely difficult, if not impossible, to administer any of the currently available standardized tests under the extreme environments involved. Indeed, as Dr. Edwin Fleishman pointed out in the same symposium, there is even a more critical need for an adequate taxonomy for describing human abilities as they may exist within these kinds of stressful environments. Similarly, a Working Group of the Armed Forces —NRC Committee on Bio-Astronautics recently concluded (16), after dwelling nearly two years on this problem, that there are no standardized performance tests available that seem to be of value in this problem.

Even under static conditions during pre- and post-acceleration exposures, it is extremely difficult to measure both physiological and psychological impairment. Fortunately, however, it is possible to develop special measures and indices which sample at least some attributes of the pilot's physiological and psychological functioning, and to concentrate on selected aspects of behavior which may be measured under both static and dynamic conditions.

THREE CLASSES OF MONITORING

From a monitoring point of view, there are three general classes of responses which may be observed during exposure to acceleration. These are as follows: physiological (biomedical), psychophysiological, and psychological. The psychophysiological category is an intermediate class which consists largely of quantities which have both physiological and psychological components. This intermediate category is justified because the dividing line between physiological and psychological components is sometimes very uncertain. These components are at times very closely dependent upon each other, and, to a major extent, related to each other.

The biomedical (physiological) class includes evidences of activity which indicate the condition of basic physiological systems, such as the cardiovascular, pulmonary, and metabolic systems. Measures of this type generally include heart activity, systolic and diastolic blood pressure, respiration, metabolism and body (core) temperature. The psychophysiological area generally includes measurements of systems which are very sensitive to both physiological as well as psychological embarrassment. Typical examples include the psychogalvanic skin response (GSR), skin temperature, electromyograph (EMG), certain biochemical reactions, the sensory and perceptual condition of the pilot, and the emotional and motivational conditions of the pilot. The psychological factors usually include the overt behavioral and response systems. They are concerned primarily with the pilot's ability to identify, discriminate, remember and to make motor responses, estimations, calculations, predictions, and decisions.

In this manuscript, the treatment of the physiological and psychophysiological quantities will be minimal. Techniques for biomedical and psychophysiological monitoring have been well covered in previous reports (17). There appear to be no comprehensive reports on the subject of psychological monitoring of subjects during exposure to acceleration stress, although the need for such procedures has been emphasized in the scientific literature (2, 26, 9, 7, and 13).

CRITERIA FOR MONITORING

In addition to the ever-present requirement of reliability and validity, there are several additional test criteria which are very important in measurement of human responses under acceleration stress. These are as follows:

(a) Provision for the continuous monitoring of physiological and psychological performance during exposure to the stress.

(b) Automatic recording of the task inputs and subjects responses so that the subject's responses are displayed in a meaningful and analyzable form with respect to the intensity, frequency, direction, and duration of the stimuli.

(c) Sensitivity to subtle impairments in performance.

(d) Known behavioral cut-off points (or behavioral tolerance limits).

(e) Task characteristics which account for the possibility of learning during repeated trials.

Ideally, the tests of performance decrement should be sensitive enough to reflect the decrement in terms of amplitude and frequency characteristics. They should measure the sensory, motor, integrative, and cognitive capacities of the subject and should provide a total task score (in addition to sub-scores) as a measure of the total functioning of the subject. Finally, the tasks should be ones which permit the simultaneous recording of physiological functioning while the subject is undergoing the stress.

These criteria are difficult to meet. In some situations it is possible to develop tests or methods which attempt to assess impairment by direct means. One may develop tests of specific functioning and abilities which may be administered to the pilot as the run proceeds. In these cases, the pilot must devote his attention to taking the test rather than to piloting, and consequently, the use of these tests in some kinds of situations is very limited. The alternative is to take performance measures on a non-interference basis. The third approach is to use the piloting task itself as a measure of intellectual and physiological functioning. In the views of the current investigators, this offers the most promising approach. In most flight simulation studies on the centrifuge, it is not possible to measure performance directly by means of specific tests, due to the fact that the astronaut must perform some piloting task. Recent studies of this problem have led to consideration of the possibility that the piloting performance task itself serves as a measure of piloting performance. These may be adapted for use in monitoring and measuring the functioning of behavioral systems of human subjects during exposure to acceleration stress. It is not possible to specify exactly what specific ability is being measured (any given task reflects a relatively large distribution of higher mental abilities), however, this technique does meet the criterion of providing total task scores, and these can be obtained at those critical points in the mission profile where measures are both most needed and least possible with standard tests.

PERFORMANCE TOLERANCE TO ACCELERATION STRESS

In addition to the physiological tolerance limits which define the endpoints for reliable functioning for any particular physiological system during exposure to acceleration stress, there are also performance tolerance limits which define the end points for reliable functioning of any particular overt behavior system during acceleration (9). The physiological and performance tolerance limits may be functionally related, but they are not necessarily the same. Performance tolerance limits usually indicate the G amplitude level or time during which a pilot may satisfactorily perform a given task. The specification and development of performance tolerance maps which show impairment as a function of physiological acceleration stress are dependent upon the identification and quantification of performance errors so that the amount of impairment of the particular human ability in question may be indicated.

Eleven different types of error performance which test pilots and astronauts frequently make during stressful portions of acceleration runs, but which they do not generally make during static control runs, are listed below. These are not specific to any particular kind of piloting tasks. Rather, it is believed that these eleven types of errors are common to piloting behavior under conditions of intense or prolonged acceleration stress. They are meaningful expressions of accuracy, speed, and consistency of behavior: (a) Increase in error amplitude, (b) lapses, or increasing unevenness, and irregularity, in performing the task, (c) performance oscillations, (d) falling off in proficiency, or a failure to respond in some part of the task, while responding or maintaining proficiency in other parts, (e) changes in timing or phasing of task components, as may occur for either a multi-dimensional task or in a sequential task, (f) inadvertent control inputs, (g) changes in the rate (or frequency) of performance, including response lags, (h) initiation of performance nonessential to the task, (i) over-controlling and under-controlling, as during a transition phase, (j) failure to detect, or inability to sense, perceive, and/or otherwise retrieve stimuli and other information, (k) errors in retrieving, integrating, storing, processing or reporting information.

MONITORING OF VISUAL PERFORMANCE

Visual disturbances occur during exposure to acceleration stress. During positive acceleration, these disturbances result primarily from ischemia, although some mechanical distortion of the eye may also occur. Generally, a period of grayout occurs before blackout. Grayout is characterized by general dimming and blurring, and total visual loss occurs approximately one G unit above grayout. Some of the major relationships among the amplitude, duration, rate of onset of positive acceleration, time to grayout, and unconsciousness were reported by Stoll (27).

When the acceleration is $+G_x$, no major visual disturbances have been reported up to loads of $+14G_x$ for 5 seconds at peak. At levels between 6 and 12 $+G_x$, there may be some tearing, apparent loss of peripheral vision, and some difficulty in focusing the eyes. For $-G_x$, vision may be temporarily impaired, some pain may be experienced, and small petechiae may occur on the lower surface of the eyelids. However, no internal damage has been reported for accelerations as high as $-15\ G_x$. The problem of seeing under transverse acceleration appears to be largely a mechanical problem, due partially to mechanical pressures on the eyes and the accumulation of tears. However, in addition to amplitude and direction of acceleration, G duration is also of major importance. Endurance time to transverse acceleration is largely dependent upon the type of G-protection which is provided to the pilot. Using the AMAL centrifuge, it has been possible to achieve endurance record runs for transverse acceleration of 127 seconds at $+14\ G_x$, and 71 seconds at $-10\ G_x$. These runs were made possible largely because of a G-protection system developed by Smedal, et al (23) and by the extremely high motivation demonstrated by the pilots who performed these runs. Moreover, the pilots were able to see a complex tracking display well enough to perform satisfactorily throughout these runs.

The pilot's ability to read instruments is influenced by acceleration. As the magnitude of G increases, visual acuity decreases (30). However, a given level of visual acuity may be maintained by increasing the size of the target or by increasing the amount of luminance. At high luminance, the impairment due to G is not as great as it is for the same G at lower levels of luminance.

As acceleration increases, an increase in contrast is required to detect a target. This has been shown in a recent study by the authors and Drs. Braunstein and White at AMAL. In this particular experiment, visual brightness discrimination was studied at four levels of background luminance, at four levels of positive acceleration, and at five levels of transverse acceleration. A stimulus display generator mounted in the gondola, presented a circular test patch against a diffuse background. The display was viewed monocularly through an aperture, and the visual angles subtended by the circular test patch and its background were 1 degree and 28 minutes, and 8 degrees and 4 minutes, respectively. The background was generated by eight 25 watt light bulbs behind two sheets of flashed opal by a 500 watt slide projector. Voltage to the projector bulb was controlled by a motor-driven variac. A neutral density filter was placed behind the viewing aperture to produce the desired background luminance. A response button, provided to the subject, was used to indicate the appearance or disappearance of the test patch. After activation of the response button by the subject, the direction of rotation of the motor driving the variac which controlled test patch luminance was automatically reversed with a random delay. At the instant of the subject's response, the voltage across the projection bulb was stored and displayed upon a digital volt meter located at the experimenter's station. Approximately 15 responses were made during the peak G of each run. With this apparatus, it was possible to repeatedly measure a subject's ascending and descending visual discrimination thresholds. Six healthy adult males with 20/20 vision were subjects. For each of four positive acceleration conditions, the mean required contrast increased as the background luminance decreased. Also, for any given background luminance level, the higher acceleration levels required more brightness contrast. Similar results were shown for the transverse G exposures, although the differences due to background luminance were more than those due to acceleration levels. Positive acceleration stress consistently imposed higher contrast requirements than did transverse acceleration.

MONITORING OF DISCRIMINATION AND RESPONSE BEHAVIOR

In addition to influencing the pilot's ability to perceive stimuli, acceleration modifies his ability to respond to them as well. Although it is generally agreed that acceleration influences discrimination reaction time behavior, it has not been possible to identify all of the underlying mechanisms which mediate these effects. During acceleration, the changes observed in reaction time may be associated with pilot impairment in a variety of physical loci. Acceleration might reduce the capacity of the peripheral system to receive the stimulus, or of the central nervous system to process already received stimuli and to indicate discriminatory choice, as well as reduce the ability of the neuromuscular system to coordinate the motor components which translate the response into the manipulation of the appropriate control device. In addition, some studies have indicated that discrimination reaction time under G is indirectly affected by the protective equipment and related components present in the situation in which the tests are conducted.

For example, suit conditions during dynamic simulation, and acceleration itself, did not affect overall mean response times to telepanel indications. However, analysis indicated that the response variability demonstrated by the astronauts was significantly increased by the acceleration condition, and by the "suit-hard" condition. Similarly, in a later study involving these same astronauts the average response time for the "suit-hard" condition was slightly greater than for the "suit-soft" condition. The average latency was 4.28 under suit-hard conditions, and 3.68 seconds during the suit-soft conditions. These differences were not statistically different. It is interesting to note that the average response times were not significantly affected by the change in altitude simulated by gondola evacuation. Here, the average override latency was 3.64 seconds at sea-level pressure (14.7 psi) and 4.68 seconds when the gondola pressure was reduced to 5 psi.

The above studies were all conducted in relatively complex Mercury simulation projects in which the pilots were performing rather complex tasks during complete mission acceleration conditions. However, in a series of basic research studies, an attempt was made to measure the effects of steady-state transverse acceleration on discrimination time without the involvement of pressure suits and gondola evacuation. A discrimination reaction time test apparatus was developed that consisted of four small stimulus lights, a small response handle containing four small response buttons, and a programmer device which could present a large variety of random sequences to subjects on the centrifuge (11). As each of the lights came on, the subject was required to press the associated finger button with his right hand as fast as he could. Both the automatic program which activated the stimulus lights and the subject's responses were fed to an analog computer where initial data reduction was accomplished. Following pre-acceleration training to establish a stable baseline performance level, each subject received three blocks of 25 trials each while exposed to $+6\ G_x$ for five minutes. Each subject received three such acceleration trials. Since speed and accuracy were both involved in this type of response behavior, times and errors were normalized and added. The results showed a highly significant effect of the acceleration on performance. Further, the effect persisted to the post-test period, although to a lesser extent. In addition, during the first block of twenty-five trials, the average response scores were slower than for the first block of trials. For the third block of trials under G, however, performance was significantly improved over that exhibited during the earlier trials. The results of this study suggest that acceleration initially impaired performance during the first and second series of acceleration trials but that by the third series of trials, the subjects had learned to maintain their physiology and performance under acceleration stress and, consequently, their discrimination reaction time scores improved, suggesting that learning how to perform during exposure to acceleration stress is a primary factor in determining pilot performance ability. It may well be that the process of learning could account for some of the differences in findings which have been reported by earlier investigators who contrasted static and dynamic conditions without taking into account the possibility of rapid adaptation to the experimental conditions. Frankenhauser (15), using red, green and white light signals, measured complex choice reaction time during exposure to $+3\ G_z$ and found the subject took significantly longer to respond under acceleration than under normal ($+1\ G_z$) conditions. This was true for exposures of both two minutes and five minutes duration. Her conclusion was that visual choice reaction time was increased by positive acceleration. Similarly, Brown and Burke (1) found highly significant effects of positive acceleration upon discrimination reaction time.

Using an auditory task rather than a visual stimulus in order to avoid the problem of visual interference which accompanies acceleration, it has been possible to obtain data on auditory reaction time at grayout levels. One such task (14) required the subject to add pairs of numbers which he heard via an auditory magnetic tape system and then to describe the sum by pressing the small odd and even response buttons which were mounted upon his left and right hand grips, respectively. Research with this apparatus during positive acceleration exposures to grayout levels indicated that the time required to make these responses increased during exposure to positive acceleration.

MONITORING COMPLEX SKILL BEHAVIOR

Skill decrement usually occurs prior to physiological decrement. For example, Figure 3 shows EKG, pulse, respiration, blood pressure, tracking efficiency, pitch error, heading error, roll control, pitch control, and yaw control, for a sustained -8 G_x centrifuge run. In this particular example, tracking efficiency was calculated in percentage units based on accumulated tracking error divided by the accumulated excursion of the target display which the pilot was monitoring. Pitch and roll control inputs were made with a small pencil controller, and proficiency could range on a percentage scale from 100% to -100%, as derived from the division of the actual control output by the required output. This figure clearly shows that the tracking efficiency took a very sudden and marked drop from nearly 90% to approximately -95% near the end of the run. Very little physiological change is shown except for a slight change in respiration. This record is one of the many instances which have emphasized the predictive value of performance scores for medical monitoring purposes, and it illustrates the detrimental effects of high sustained acceleration on psychomotor skill performance.

Studies of pilot performance during staging acceleration profiles, such as may be characteristic of certain two-stage and four-stage launch vehicles, have suggested that at the higher acceleration levels, pilots find it extremely difficult to concentrate on all aspects of a complex task while they are exposed to high acceleration loads, whereas at the lower acceleration levels, they can perform very well. In one study pilots performed exactly the same tasks statically and dynamically for each of two types of booster combinations. The pilot's task was to perform the four aspects of the task contin-

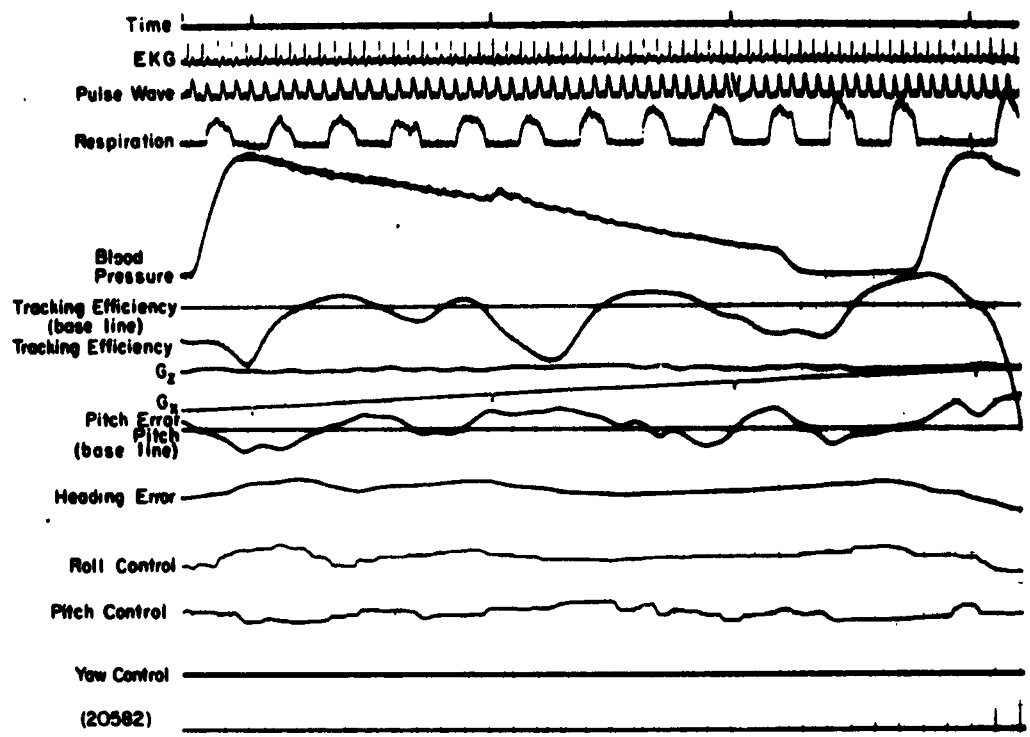

Figure 3. Example of physiological and performance measures recorded under sustained $-8G_x$.

uously so as to fly the vehicle through the orbital injection "window". For both types of vehicles, it was found that the pilots made significantly more errors on the yaw quantity during dynamic conditions than during static conditions, but that they were able to maintain the other three task components very well under both dynamic and static conditions. In this particular study, the accelerations did not exceed 7 G_x for either type of vehicle.

During reentry simulations of the Atlas vehicle on the human centrifuge, inadvertent control inputs were not uncommon. These inadvertent inputs often mirror the acceleration profile under which a control task is being performed.

In addition to inadvertent inputs which accompany acceleration, other more general effects of dynamic conditions may be observed. Acceleration appears to reduce generally the sensitivity and timing of all controller movements.

A series of Military Astronaut Training Programs (MATP) has been conducted at AMAL in cooperation with the USAF Aerospace Research Pilot's School. In this series the students and instructors of the school have received orientation to acceleration experience while serving as pilots for research studies on the centrifuge.

During the MATP II, the Engineering Psychology Laboratory at AMAL provided a task representing an undamped vehicle with 3-axis proportional control, with large low-frequency disturbances. The pilot's task was to damp rates, which were presented as an integrated display on a TV monitor. A 3-axis finger-tip controller of Grumman Aircraft design was used, mounted in-line with the pilot's forearm, rather than perpendicular to it. Errors and stick movements in the three axes were recorded on strip charts. Positive errors, negative errors, errors squared were integrated, recorded on strip-charts, and printed out in decimal digit form on paper tape.

Different types and durations of centrifuge runs were used. The major division as to type of run was between the time-varying and steady-state accelerations. The time-varying profiles consisted of shortened simulations of the Mercury-Redstone and Mercury-Atlas missions.

The steady-state runs had a constant rise-time of 15 seconds to peak, 125 seconds at peak, but shorter periods were used for particularly stressful acceleration vectors.

The display for these programs was presented on the face of a Sony TV monitor, and consisted of an unmoving X-Y reference grid, and an inverted "T" figure. This figure was capable of ± 2" of movement in X and Y axes, ± 180 degrees of rotation. The display was located approximately 22 inches from the subject's eye and was set at 90 degrees to line of sight, which was 20 - 25 degrees below the horizontal. Picture resolution, due to degraded response of the Dage TV camera, was a fairly serious problem, and this variability undoubtedly caused an increase in experimental error.

Figure 4 shows the block diagram of the system used for both programs. Low frequency mixed sinusoid disturbances were introduced at the block labeled "Task Dynamics", as were the pilot's control actions. This was a first order system (single integration), so the pilot was damping "rates" produced by the disturbing "accelerations". The instantaneous rates were scaled and/or transformed, combined with constants required to generate the display, and commutated to a single-beam X-Y oscilloscope. A TV camera then transmitted this display to the TV screen in the centrifuge gondola. The pilot, viewing this display, manipulated the three-axis controller to minimize these errors.

The pilot's control movements and the system errors were recorded on multi-channel strip-charts. In addition, the instantaneous errors were split into positive and negative components, and separate time integrals were produced, recorded on strip-charts, and recorded digitally. A standard 30-second period of integration was used, and the values of the integrals were tracked until t_{30}, at which time the values were held for automatic digitization and print-out. As the track and hold circuits were put to "hold", the integrators were momentarily placed in reset, and then began a new integration. After readout by the Data Logger of the hold circuits, these circuits again began to track the integrator outputs.

Figure 5 presents a summary of pilot performance in this program on 118 runs. A single value representing error was derived for each subject (student or instructor) for each steady-state centrifuge run. To derive these values, integrated errors were summed without respect to axis or sign, and this sum was divided by the number of 30-second scoring periods in the run. Linear estimation was used for conversion of non-standard periods to the 30-second standard, and to estimate the value of off-scale integrals. The means plotted in Figure 5 are the means of these error scores, so equal weight is given to each run.

MATP III has just been completed. A two-axis task was used, with a vertically mounted finger-tip controller, but in other respects the task was quite similar to that used in the previous program.

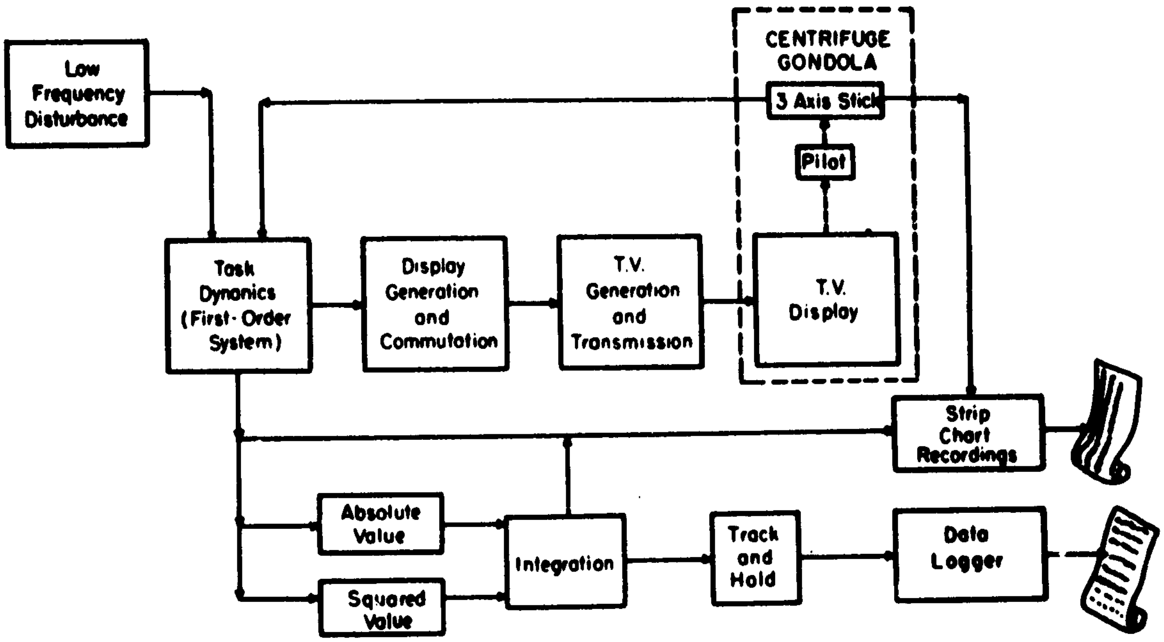

Figure 4. Diagram of system used to provide piloting task and to process and record performance data during Military Astronaut Training Program II.

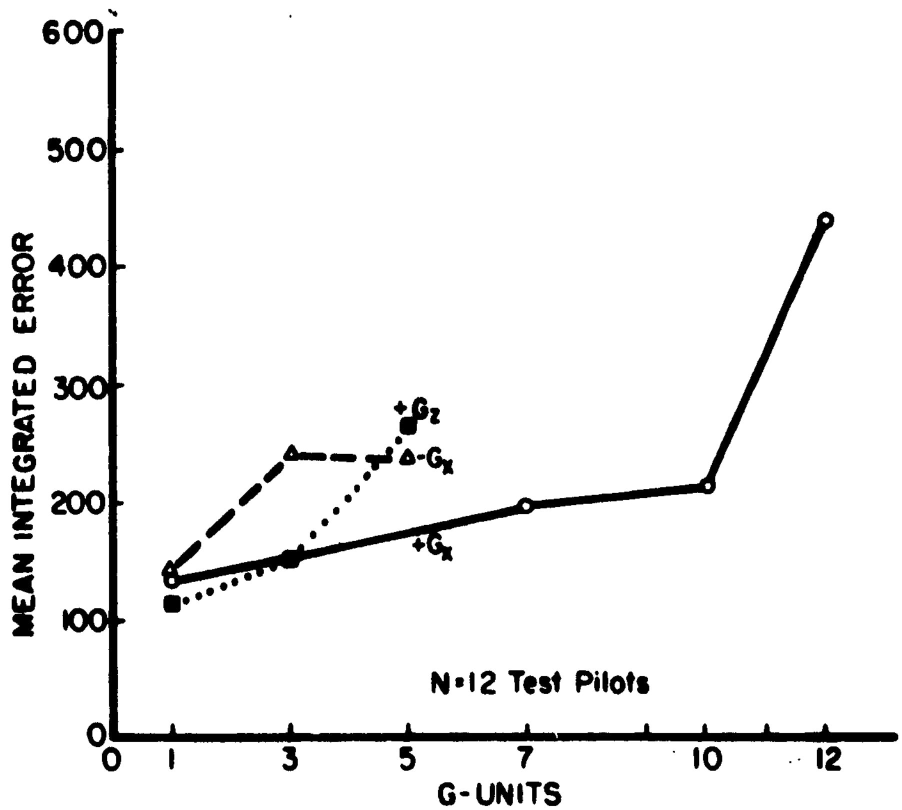

Figure 5. Comparison of the effects of direction and amplitude of acceleration upon pilot error in a three-axis rate-damping task.

An examination of specimen records from this project indicated that the stick rate (time differential of stick position) may be a very useful monitoring variable. Changes in its frequency/amplitude characteristics appear to be quite stress sensitive, and appear earlier in the run than do easily discriminated system errors. In addition it quickly displays "dead stick" conditions. Since the Medical Monitor will stop the run upon this indication of unconsciousness, pilots will move the stick even when they can no longer fly the task, so as to indicate continuing capability for muscular control.

MONITORING HIGHER MENTAL FUNCTIONING

Review of the problem of measuring the effects of acceleration on higher mental functioning (16) indicates that there is a severe lack of technology in this area. It is generally accepted that exposure to high or prolonged acceleration may produce confusion, unconsciousness, disorientation, memory lapses, loss of control of voluntary movements, or prolonged vertigo. However, to date, there is very little quantitative data regarding the effects of acceleration on specified intellectual functions. At AMAL, emphasis in this area has been concentrated on immediate memory.

In a recent study, conducted in cooperation with Rutgers University on the AMAL centrifuge (22), we developed a task which required the subject to monitor two small display tubes which were located directly in front of his normal line of vision. The left-side tube presented numbers, and the right-side tube presented plus and minus symbols. The task was to continuously make matches for these two presentations simultaneously as the runs proceeded and to select one of two buttons to indicate whether both the number and symbol which were then appearing were the same as or different from those which had occurred on a specified number of trials previously. Acceleration loads of 1, 3, 5, 7, and 9 G's were studied. Each test was 2 minutes and 18 seconds long. The results of the experiment suggested that proficiency in immediate memory was maintained at least through 5 transverse G. However, at +7 and +9 G_x, some impairment of immediate memory was observed.

EFFECTS OF PROLONGED LOW-G ACCELERATION

During prolonged exposure to acceleration, the continuous concentration necessary for performance is difficult, fatiguing, and boring. For example, during an extended 2 G centrifuge run which lasted 24 hours, the subject started out with a somewhat detailed set of procedures to follow in making medical observations upon himself, recording his subjective comments, and writing and typing (12). However, the subject found that, in spite of his initial high resolves, he took naps and listened to the radio and suffered primarily from boredom and fatigue. Areas of contact with the chair in which he was seated were the sources of the greatest localized discomfort. At 16 hours elapsed time, the subject reported the onset of aesthenia of the ring and little finger and outer edge of the palm of the left hand. The subject found it impossible to maintain his originally prescribed maintenance and observation schedules.

Chambers and Ross secured a subject in a Mercury-type contour couch and required him to perform the two-symbol running matching memory task (previously described) every 10 minutes for four and one-half hours. At $+2\ G_x$ the subject was able to perform this task throughout the entire period with only minor performance impairment.

INTERACTION EFFECTS

It has been shown that the human centrifuge is a useful tool for measuring the interaction effects of several variables simultaneously. In addition to both the direct effects of acceleration upon human performance and the less obvious interactions between performance and acceleration already mentioned, there is a growing body of information pertaining to the somewhat secondary role that other flight conditions play in determining a pilot's performance during acceleration stress. For example, in the early simulations of proposed space vehicles, several types of right hand side-arm controllers were tested on the AMAL centrifuge (5): I. A three axis balanced controller with all three axes intersecting; II. a three axis controller (unbalanced) having none of these three intersecting; and III, a finger-tip controller having two intersecting axes (and yaw for toe pedal operation); and IV, a two axis controller with axes which do not intersect (coupled with toe pedals for yaw control).

In Figure 6 the effects of two specific acceleration fields upon pilot performance during the pitch and roll maneuvers involved in a tracking task are shown for each of the four types of controllers. When the pilots performed in one acceleration field, their error performance on all four controllers was essentially the same. However, when these same pilots flew the same problem under a different acceleration, performance on Type II controller deteriorated while performance on the other three remained essentially the same. A similar change in G field resulted in an increment in error for Types II and III controllers and reduction in

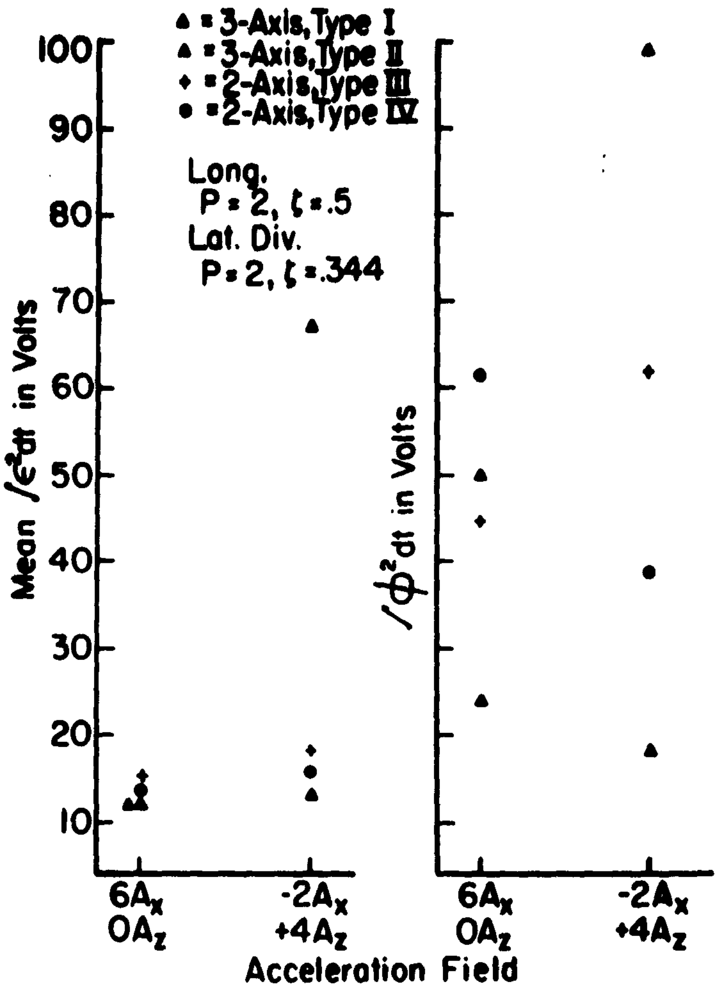

Figure 6. Performance error in different acceleration fields as a function of the type of controller used.

error for Type IV, resulting in a shift in rank order of the controllers. The differential effects upon performance induced by different types of acceleration on controllers are shown in Figure 7. There the mean tracking proficiency score for the test pilots who performed the same tracking tasks using each of the four different types of side-arm controllers within given acceleration fields and under varying amounts of cross coupling and damping are shown. This figure shows not only the effect of using different specific G fields on particular tracking tasks, but also illustrates the effects of damping and cross coupling when the effects of acceleration are held constant.

A similar type of result may be shown which resulted from some of the Mercury astronaut training programs on the AMAL centrifuge. In some of these simulations it was observed that the tendency to use less discrete, more frequent control inputs under dynamic conditions was associated with an overall increase in fuel utilization. A most important aspect of this relationship depends upon the fact that differential rates of fuel usage were observed even when no significant differences in adequacy of control as measured by integrated attitude error were present. As previously indicated, pilot ability to damp the reentry oscillations in pitch and yaw was reduced under dynamic simulation. In contrast, control capability in the roll axis was not significantly affected by dynamic reentry accelerations. Therefore, roll control during reentry can be used to compare this dynamic effect under conditions of equivalent error. Comparison shows that fuel utilization was approximately 33% greater under dynamic than under static condition, though integrated error was of the same approximate magnitude under both conditions. Data of this nature emphasize the advisability of obtaining both dynamic and static performance before placing estimated values upon such design parameters as required fuel reserves.

As another example of interaction effects regarding pilot performance, it was found that hard-suit (5 psi differential pressure) conditions resulted in a reduction in relative piloting performance during static simulation of the reentry control task, but appeared to assist performance under dynamic conditions. The measure used was the percentage of reentry simulations in which capsule oscillations were successfully damped. The performance values are not absolute but they represent relative performance using the conditions of static soft-suit, under which control must often be retained throughout the reentry profile, as a base-line referent. The additional forearm support provided by the pressurized suit appeared to reduce the frequency and/or magnitude of the previously described inadvertent inputs which accompanied dynamic simulation. As the tendency to insert such inputs was reduced through practice, the stabilization provided

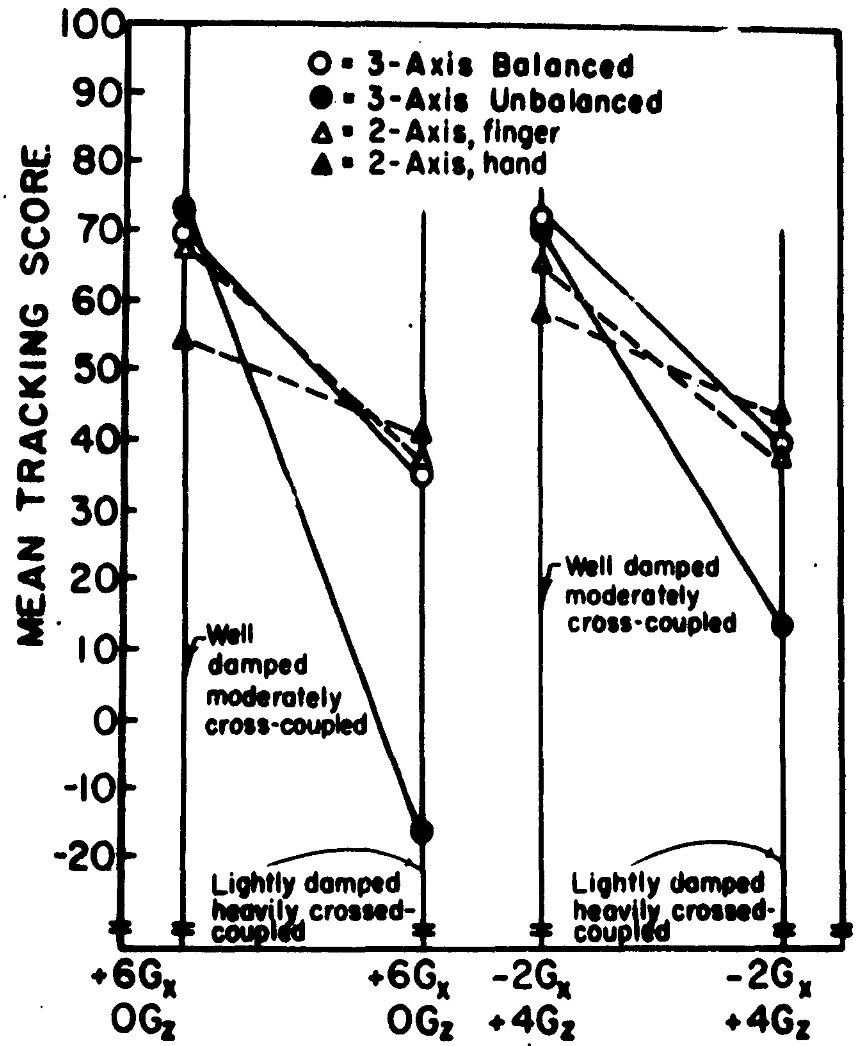

Figure 7. Mean tracking score for three-axis balanced, three-axis unbalanced, and two-axis finger and two-axis hand controllers.

by the inflated suit appeared to become less and less of an advantage and the interaction between suit and run conditions was markedly less during the latter stages of training. Verbal reports obtained toward the end of the training program indicated that the pilots considered suit-hard conditions more uncomfortable and perhaps even less effective.

DISCUSSION

In the selection of performance tasks to measure decrement under accelerative stress, a recurring problem is the definition of "error" and the comparison of errors across time when task difficulty level is at least partly a function of time. In certain types of tasks, the definition of "error" presents no problem. In a pure tracking task (zero order control system) the pilot is required to function as a simple amplifier, and error is easily defined, although its significance may be problematical.

However, when the pilot is given a vehicle (simulated or real) to fly, and is provided with displayed flight quantities, a control device, and a set of instructions, it will ordinarily be the case that only a small portion of his responses can be categorized as correct or incorrect. If the pilot's task is to maintain a specified roll rate, and minimum fuel usage, "error" would occur only when fuel is used to increase rate error. When the task is to maintain a specified attitude, while minimizing rates of fuel usage, unequivocal error is even more limited. The pilot must process information concerning attitude error, rate, rate of change of rate (differentiation of rate by pilot), stick position, and perhaps even external accelerative forces (difference between observed and expected rate of change of rate, based upon stick position). His task is to make such stick movements as are required to bring attitude error and vehicle rate to zero at <u>some</u> same future point in time. He can come in fast (high fuel usage) or slow (larger mean and higher peak errors). He may use a series of high amplitude and short duration pulses, or a low amplitude continuous input. During the period of this correction, any amplitude is correct.

Another aspect of this problem is the requirement for assessing changes in performance capabilities from one point in time to another, when task difficulty level, and perhaps even the nature of the task, is changing over time. In space vehicle full mission simulations this problem becomes quite serious.

One approach to these problems involves the fairly simple expedient of looking for performance error, or at least some diagnostic changes in performance, at points closer to the actual performance. That is, supplementing system error information with information concerning the nature of the performance, and changes within the performance that produced the observed system error. Such measures might include, but need not be limited to, stick rate, integral of absolute value of stick rate, stick position, and absolute integral, differential of all displayed quantities and absolute value integral of each, and vehicle accelerations of external origin. Experience at AMAL during the Military Astronaut Training Program III indicates that rather large changes in some of these variables may occur under acceleration stress, and may have little or no effect on system error.

A second approach involves the use of models. The assumption here is that there are a limited number of types of control systems that a pilot may approximately mimic, and there are also a limited number of systems that could replace the pilot in the control loop and keep the system under control. If repetitive computations were made to determine what type of control system the pilot was acting as, and to what extent he was acting as no acceptable control system would act, then two types of measures would be available. We would have a measure of his "error", and we would also have information as to what sort of system he was acting as, and whether and when his mode of response began to mimic another system.

A third method of performance assessment that should be considered is that of record oomparison. In this method, a series of records would be combined, and then the new performance would be compared with the standard derived from the previous data. This approach seems most promising for real time monitoring of pilot performance where vehicle cost is high, number of pilots in program small, and piloting tasks quite varied over the mission time. One important advantage of this technique is that it permits comparison of a pilot against his own norm, and so would immediately call attention to any deviation from the expected, even though this deviation might not initially be considered important. The greatest difficulty with this approach is its complexity. The number of ways in which a record of one variable can differ from another record of that variable is quite large, and when a large number of variables are involved, simple additivity gives an almost unmanageable complexity. When consideration is given to interrelationships between variables, it is obvious that considerable selectivity must be exercised. It is currently planned to apply these techniques in future programs at AMAL.

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1. Psychophysiology
2. Bioinstrumentation
3. Human Factors
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5. Acceleration
6. Performance
7. Monitoring

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